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DTU PMU Laboratory Development – Testing and Validation

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***Abstract*-- This is a report of the results of phasor measurement unit (PMU) laboratory development and testing done at the Centre for Electric Technology (CET), Technical University of Denmark (DTU). Analysis of the PMU performance first required the development of tools to convert the DTU PMU data into IEEE standard, and the validation is done for the DTU-PMU via a validated commercial PMU. The commercial PMU has been tested from the authors' previous efforts, where the response can be expected to follow known patterns and provide confirmation about the test system to confirm the design and settings. In a nutshell, having 2 PMUs that observe same signals provides validation of the operation and flags questionable results with more certainty. Moreover, the performance and accuracy of the DTU-PMU is tested acquiring good and precise results, when compared with a commercial phasor measurement device, PMU-1.**

***Index Terms*—phasor measurement units, IEEE C37.118, synchronised phasor, universal coordinated time (UTC).**

I. INTRODUCTION

SINCE phasor measurement unit (PMU) technology was developed and introduced into the power system in the early eighties, and it has demonstrated large advantage to traditional SCADA systems. This fact comes due to its high-speed and time synchronized capability on measurement [1-2].

The phasor measurement technology has a unique capability of sampling analogue voltage and current signals in synchronism with the Global Positioning System, GPS, as well as converting the analogue signals into phasors (synchrophasors). The current IEEE Standard C37.118-2005 [3] determines how the information about phasors should be forwarded from PMUs to phasor data concentrators (PDCs), where the user can analyze, visualize, or use the data for specific applications. This standard also defines the steady-state performance, sampling frequency and frame format requirement for PMUs, and perspectives on dynamic tests for the future development.

The Centre of Electric Technology (CET), from the Technical University of Denmark (DTU), has developed a phasor measurement unit, called the DTU-PMU. A simple assessment and comparison of this device with a commercial PMU is done. The paper is to present the laboratory setup of the CET-DTU and to create an experimental research platform for developing and testing the synchrophasor technology.

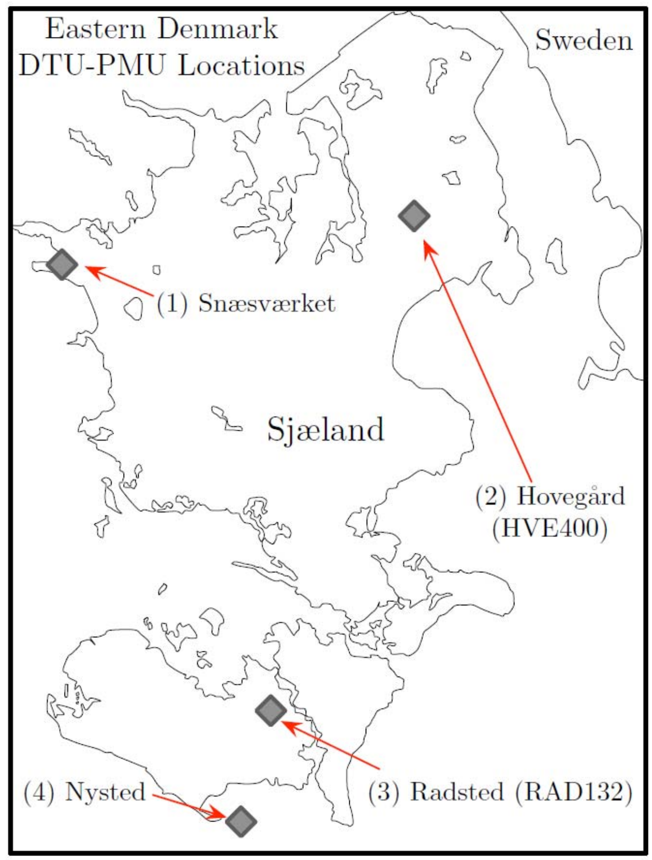

Figure 1. Deployment of the DTU-PMU in Denmark

II. DTU-PMU AND ITS DEPLOYMENT IN THE DANISH GRID

A brief description of the Danish electrical system and the DTU-PMU installation status is given below.

A. The Danish Electric Power System

The Danish power system is divided in two parts, Eastern and Western grids. Each of these parts belongs to different synchronous AC systems. The Eastern Danish system belongs to the Nordic system (previously Nordel), while the Western system belongs to the continental European system (previously UCTE (Union for the Coordination of Transmission of Electricity). The power systems in Eastern and Western Denmark have several important differences. On Sjælland the 132kV transmission network consists of ring connections, while the 400kV grid is characterized by a radial

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structure. The transmission grid in Eastern Denmark comprises overhead transmission lines and underground cables at the two highest voltage levels of 132kV and 400kV, and the interconnections with South Sweden and Germany. In Jylland and Fyn, the 400kV network is a combination of ring connections and radial structure. The 150kV grid is a parallel network which also plays a role in connection with the international transmission capacity market. The electric power transmission system in Denmark has always been divided by the Great Belt between Sjælland and Fyn, but there are plans to connect the two transmission systems with a DC cable.

B. The DTU-PMU

This unique phasor measurement device consists of two PC units that combine to perform a PMU function. One PC unit runs only the disk operating system (DOS) for reasonable handling of holds from administrative peripherals, such as timer, keyboard, USARTS (Universal Synchronous/Asynchronous Receiver/Transmitter), direct memory access (DMA), etc., and the second system has a Windows 2000 OS used for administrative tasks, such as data I/O, file creation and storage, etc. An illustration of the measurement procedure is shown in Fig. 2.

To obtain accurate phasor estimates, the PMU estimates the frequency of the AC power input signal and synchronizes sampling with it. Synchronizing the sampling to the actual power system signal eliminates problems in phasor estimation. 64 or 128 samples over the fundamental frequency period are taken with a 16-bit A/D converter. The phasor is calculated with a Goertzel algorithm, which is a simplified FFT analysis that only extracts the fundamental frequency component. The next task is translating the phasor to the UTC time reference. In addition to keeping an internal frequency estimate, the PMU also synchronizes an internal clock with the external UTC time derived from GPS clock that is synchronized to the GPS receiver. The GPS will latch and report a time stamp based on a signal from the PMU. This allows the PC to synchronize its internal time clock within 1 μs of UTC time, based on the GPS accuracy of ±100 ns. Synchrophasor reporting is based on UTC time intervals. After each phasor is calculated, the PMU compares the phasor estimate time with the UTC time. If it is time to report a synchrophasor, the PMU estimates the UTC referenced phase angle and magnitude from the 1 or 2 phasors proportionately that cover the interval. All data is stored locally; there is no real-time data output in this version. Data files can be remotely downloaded without interrupting data acquisition and storage. The main characteristics of the DTU-PMU are:

• 16 channels sampling at a rate of 1600 Hz
• 300 ns time stamp for each sample
• FFT analysis for 50 Hz component
• Phase accuracy of ≈ 0.5 μs (≈0.01 degree)
• Data collection through the Internet
• Uninterrupted local data storage on the PC's hard drive
• Transmission of one data package for each 20 ms in UTC time

C. DTU PMUs in the Danish Grid

Ten PMU devices were manufactured and placed in different locations around the Danish power grid using the phasor measurement technology discussed above. Fig. 1 shows the location of the DTU-PMUs installed in Sjælland. The distribution of the PMUs is as follows:

(1) One PMU at Snæsværket (400kV)
(2) Two PMU in Hovegård (400 and 132 kV)
(3) One PMU in Radsted (132 kV)
(4) One PMU in Nysted (165 MW offshore wind farm)
(5) One at the CET-DTU (0.4kV) - not shown in Fig. 1

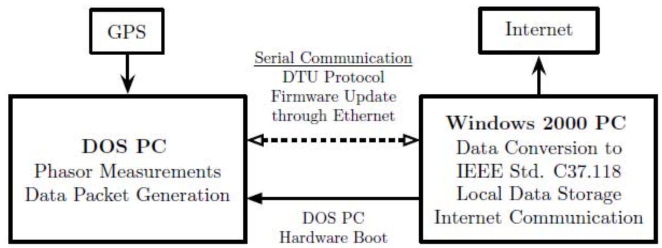

Figure 2. The DTU PC-based PMU

III. The DTU PMU Testing Laboratory description

The CET-DTU has developed a PMU testing laboratory elaborated on the authors' previous effort [4]. The signals of test plans can be generated from software. Here, the signals are generated from Matlab and converted to IEEE Comtrade file [5] format before presenting to the signal generator. The signal generator is the main equipment in this platform and requires time synchronisation capability to play back the signals with UTC time stamps to PMUs. The measurement from PMUs is collected via Ethernet to a PC. The data are stored in PC every 5 minutes under IEEE C37.118 format [3]. The principle of the tests is varying the basic parameters, amplitude, frequency and angle, of the sinusoid signal, to verify the accuracy and response of the PMU under steady-state and dynamic situations. So far, the main tests include,

1. Steady-state test
2. Modulation test
3. Dynamic test and harmonic rejection

A brief description on each test is given below.

A. Steady-state test

The fundamental parameters of a sinusoid waveform are amplitude, phase angle, and frequency. The principle of this test is incrementing one parameter while keeping other two parameters constant. This test validates the response and accuracy of PMU under different steady-state conditions. The test signal examples of amplitude and phase angle tests are described in Figs. 3-4.

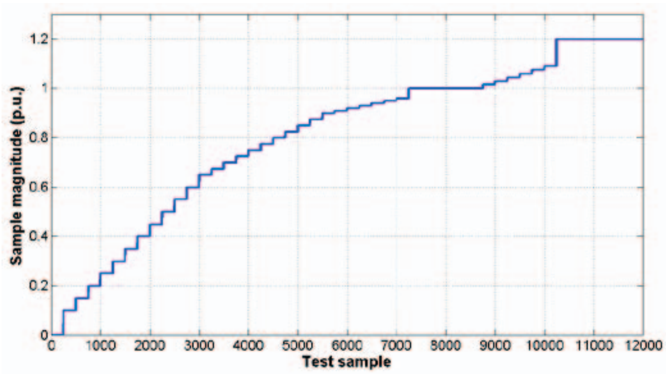

Figure 3. Amplitude scan test signal.

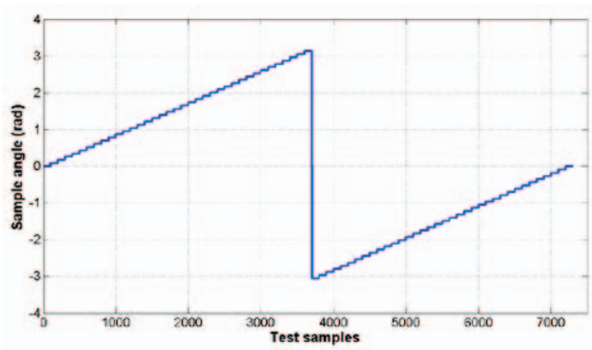

Figure 4. Phase angle test signal.

B. Modulation test

Other than the steady-state test, the principle of this test is varying one fundamental parameter with slow dynamics while other two parameters are kept constant to validate the PMU performance under quasi-steady-state conditions. An example of amplitude modulation test is given in Fig. 5.

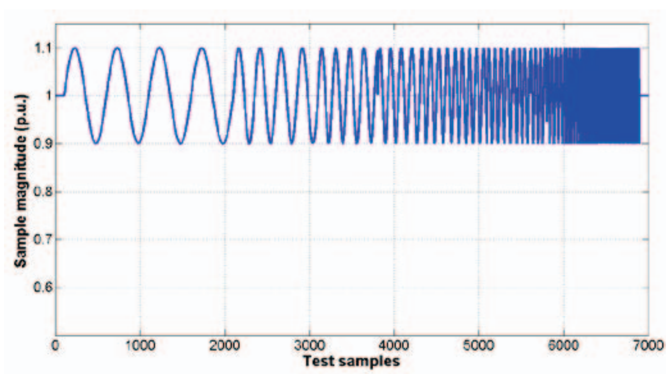

Figure 5. Amplitude modulation test signal.

C. Dynamic test and harmonic rejection

Dynamic test validates the PMU response and accuracy under the dynamic change of signal parameters. Step response test is developed for amplitude, phase angle and frequency. For harmonic test, the test signals contain the harmonic frequency from 2 to 50 orders at nominal and off-nominal base frequencies. An example of amplitude step test is shown in Fig. 6.

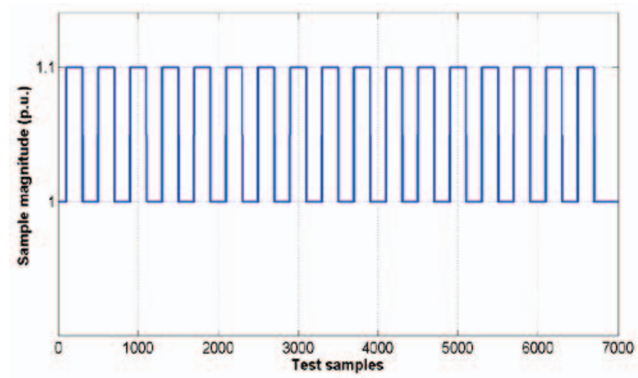

Figure 6. Amplitude step test signal.

The Total Vector Error (TVE) criteria describes the error between the actual and the measured value of the input signal. Reference [3] describes among others the maximum threshold of 120% V_n or I_n. Up to this threshold a TVE of 1% must not be exceeded.

The TVE is defined as follows:

$$TVE = \sqrt{\frac{(Xr(n) - Xr)^2 + (Xi(n) - Xi)^2}{Xr^2 + Xi^2}} \quad [1]$$

where:
$X_{r(n)}$ = real part of the input signal,
$X_{i(n)}$ = imaginary part of the input signal,
X_r = real part of the measured signal,
X_i = imaginary part of the measured signal.

Currently efforts are given to develop and extend the tests conforming to the new standard using the Total Vector Error (TVE) criterion. However, for the amplitude scan test the TVE criterion described above has already been implemented.

IV. CET-DTU Test Set-up

The physical setup requires connecting voltage and current outputs of the Doble unit to the test unit. It also requires the digital indications from the test set to be connected to the digital inputs on the PMU as shown in Figure 6. The logic outputs of the Doble produce a maximum of 25V, so the battery input is used in series to increase the voltage. In this setup, startFlag will be read on digital channel 1 of the PMU, and sampleFlag will be read on channel 2. If several PMUs are tested together, only 1 has to have the digital track. It may be best to put it into each one for later comparisons and to be sure the samples and signals match.

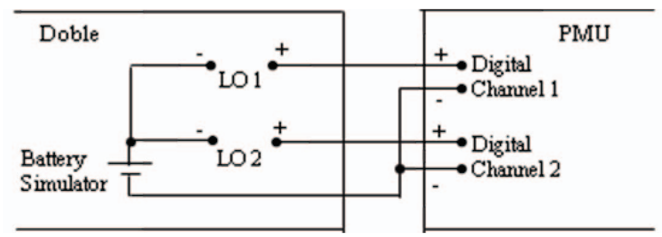

Figure 6. Setup of Doble Digital Signals with PMU (LO = Logic Output)

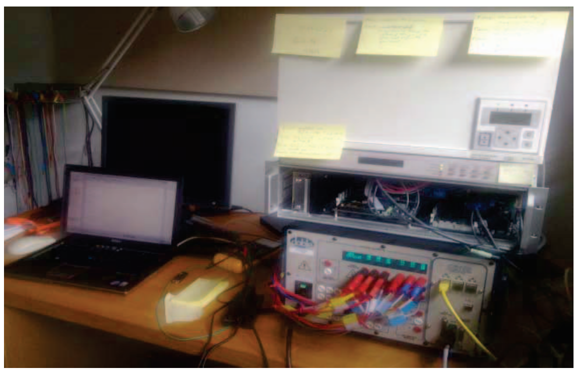

Figure 7. PMU Laboratory Setup at the CET-DTU.

V. Creating the Playback Test Files

To perform tests using the Doble playback feature, it is necessary to create signal files in a COMTRADE format. This is an overview summary of the involved process. The desired test signal is modeled using a phasor equivalent representation. The equations for the actual waveforms are written in a Matlab along with code for recording the output. Running the Matlab file produces a 3-phase signal equivalent that is recorded in a *.mat data file. This file is named according to a convention and the name is provided from the *.m file. Another Matlab file is used to translate the data file into three COMTRADE files: a configuration file (*.cfg), a data file (*.dat), and a header file (*.hdr). These tests require a three-phase analog signal (VA, VB, and VC) and two single-bit digital flags (startFlag and sampleFlag). A three phase current can also be added. The start flag is used to indicate the beginning of the test, and is enabled when the frequency of the test signal is non-zero. The sample flag indicates the middle of the dwell at a particular frequency, and is used as a reference for reading a phasor measurement. Output results are only plotted at a rising edge of the sample flag when the start flag is enabled.

VI. The Performed Tests

In this paper, initial results on 3 different tests are reported to confirm the test setup and the DTU-PMU performance:

1. Steady state tests
    a. Amplitude scan (Ascan) using the TVE criterion.
    b. Phase angle scan (Pscan),
2. Dynamic test
    a. Amplitude step (Astep).

A. The amplitude scan test.

The following figures depicted the TVE error for the voltage and current magnitude for the DTU-PMU and PMU-1 under the amplitude scan test.

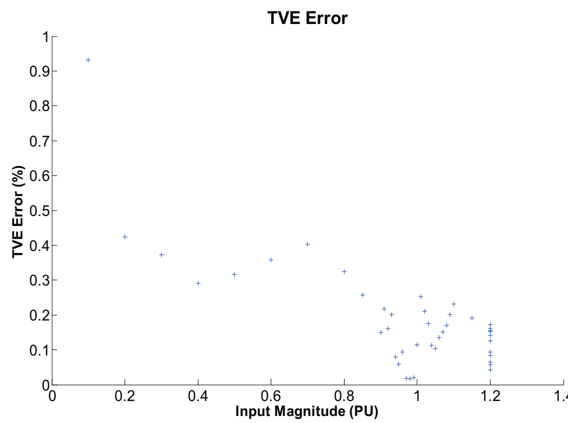

Fig 8. Voltage magnitude for the DTU-PMU.

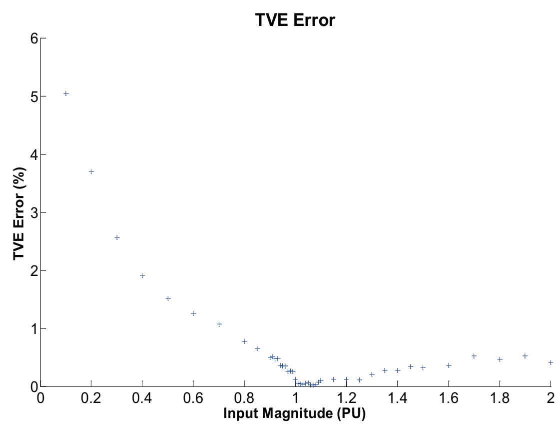

Fig. 9. Current magnitude for the DTU-PMU.

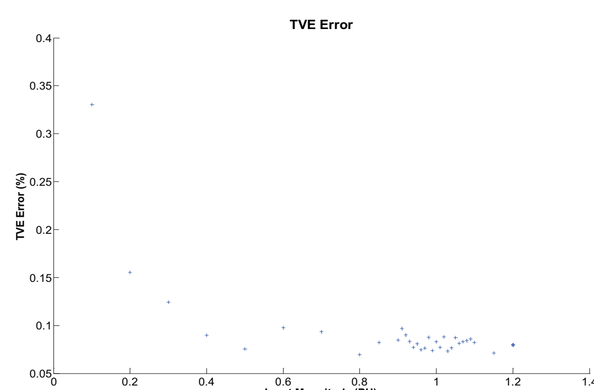

Fig. 9.Voltage magnitude for the PMU-1.

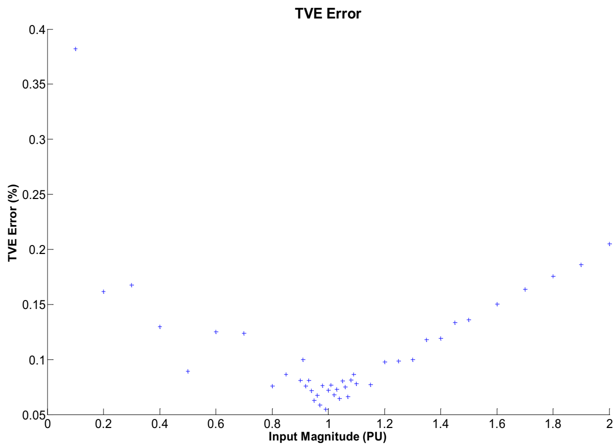

Fig 10.Current magnitude for the PMU-1.

The error shapes for both PMU-1 and DTU-PMU are comparable. For voltage, the DTU amplitude is a little high, but is within 1% for all values. The phase angle often drops off at low input values which is likely why TVE becomes higher at low values. This drop off at low values is more clearly seen in the current, where TVE increases to 5%. The error due to amplitude only (not shown here) is centred near 0, so the scaling is near optimal, so the high TVE error is due to phase angle measurement. The same patterns are seen for PMU-1 though only reaching 0.33 % for voltage and 0.4% for current..

B. *Phase angle scan test*

The phase angle is measured relative to GPS, so the test signal has to be accurately synchronized. The test set output relative to GPS was measured with an oscilloscope synchronized to GPS and was found to have a delay. Therefore, calibration of instruments is required before the test is completed.

The PMU-1 is very accurate with the added correction, < 0.1 degrees, see Fig. 11-12. This confirms the accuracy of the test signals. In general, the DTU synchronizes to the signal and tracks changes very precise and the measurements seem reasonably robust, see Figs. 13-14.

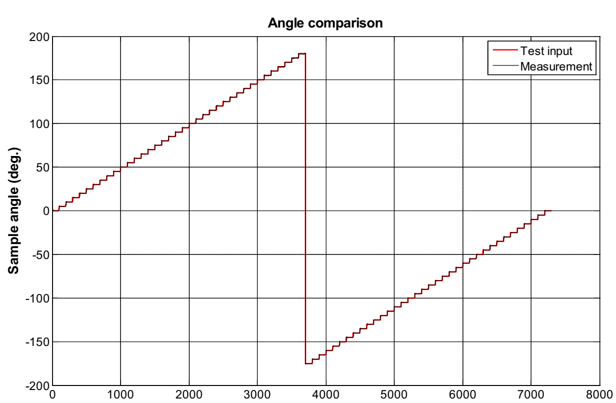

Figure 11. Overview of phase angle scan test on PMU-1.

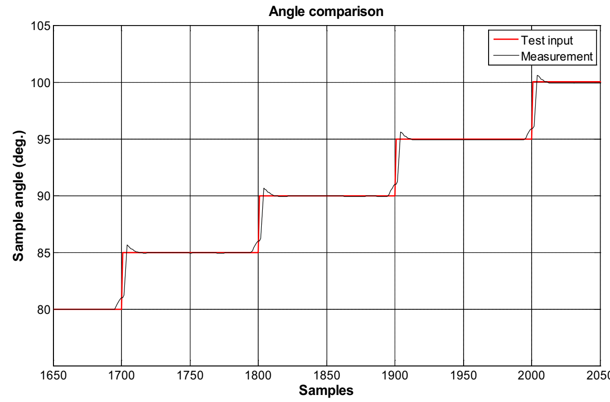

Figure 12. The response of PMU-1 in phase scan test.

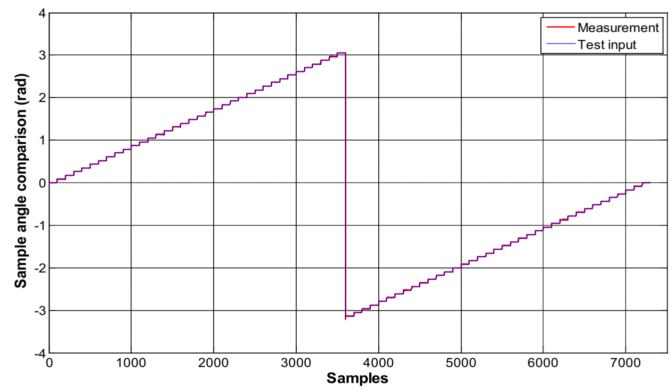

Figure 13. Overview of phase angle scan test on DTU-PMU.

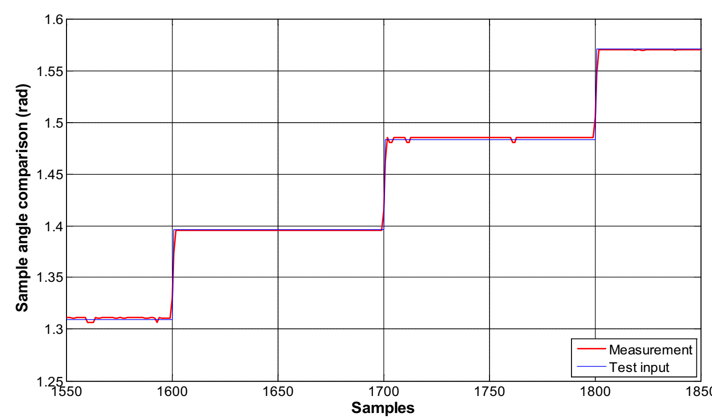

Figure 14. The response of DTU-PMU in phase scan test.

C. *Amplitude step*

A 0.1 pu positive step was used; the negative step was not used. Both the PMU-1 and the DTU-PMU responses look fairly normal. The PMU-1 was set to filter 4 which has a slow response as shown in Fig. 15. The DTU-PMU fully responds in about 40 ms (2 cycles). As depicted in Fig. 16 the performance of the DTU-PMU follows the amplitude step pattern with a minimum error < 1%.

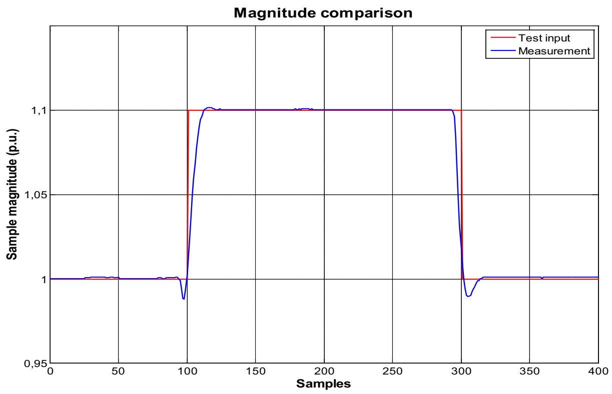

Figure 15. The response of PMU-1 in amplitude step test.

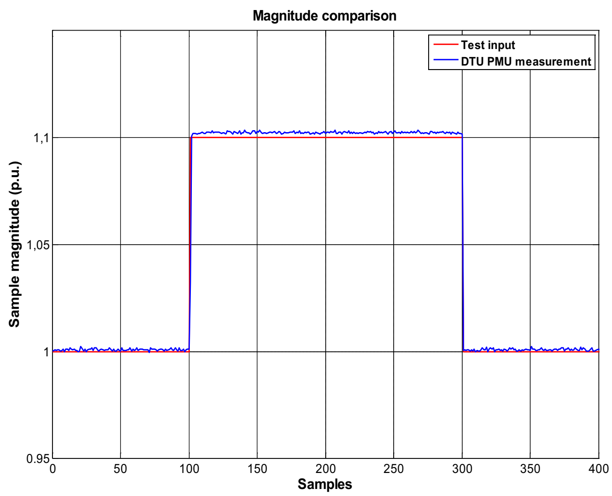

Figure 16 . The response of DTU-PMU in amplitude step test.

VII. Conclusions

In this paper, the main components of the CET-DTU Laboratory for Synchronized Measurements are presented. Preliminary testing results of comparison of the DTU-PMU and a commercial phasor measurement device conforming to the IEEE standard are presented. Three playback tests are presented and carried on for the both measuring devices, the DTU-PMU, and the PMU-1. The test results confirm the validation of the test setup and the performance of DTU-PMU. From the three selected tests, it can be seen that the DTU-PMU has a reasonably good accuracy and robust behaviour for the tests done so far. In the future, tests will be implemented on modulation tests conforming to the new IEEE standard.

VIII. References

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[5] IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems, *IEEE Std C37.111-1999,* 1999.

IX. Biographies

Rodrigo García-Valle (M’08) received the electrical engineering degree from the National Polytechnic Institute of México, in 2001, the M.Sc. degree from CINVESTAV, Guadalajara, México, in 2003 and obtained his Ph.D. degree from the University of Glasgow, U.K., in 2007. In 2008, he was granted with the Hans Christened Ørsted Award at the Centre for Electric Technology (CET) by the Technical University of Denmark to carry out postdoctoral research activities. Since 2009 he holds the position as Assistant Professor. His research interests are dynamics, stability and control of electric power systems; artificial intelligence techniques; renewable energy integration; and modeling and simulation of FACTS and custom power controllers. He is an IEEE, IET and CIGRE member.

Guang-Ya Yang (M’09) received PhD from The University of Queensland (UQ), 2008. Currently he is working with the Centre for Electric Technology (CET), Technical University of Denmark (DTU) as a Postdoc researcher. His research areas are wide area monitoring and protection system, stability analysis, and application of optimisation techniques in power systems.

Kenneth E. Martin (F’08) is a consulting eigineer at the Electric Power Group (EPG) in Pasadena, California where he develops and supports phasor measurement systems and applications. He was a Principal Engineer at the Bonneville Power Administration prior to joining EPG.. He has authored or coauthored over 50 technical papers in his specialty areas. Mr. Martin is a member of the IEEE Power System Relay Committee and the Relay Communications Subcommittee. He chairs the Synchrophasor Standard working group and the IEC 61850 synchrophasor task team, and is a member of the North American SynchroPhasor Initiative team. He is a registered Professional Engineer in the States of Washington and Oregon, USA.

Arne H. Nielsen is Associate Professor at Centre of Electric Technology, DTU Electrical Engineering. He has 30 years experience in electric power engineering; the first years from ASEA AB, Central Research and Development Department, Sweden working with measurement technology and motor design and control. During the latest 10 years his focus has been on electric power systems; especially on implementation of renewable energy sources in the power system.

Jacob Østergaard (SM’10) is Professor and Head of the Centre for Electric Technology, in the Department of Electrical Engineering, Technical University of Denmark. His research interests include integration of renewable energy, control architecture for future power system, and demand side. Professor Østergaard is serving in several professional organizations including the EU SmartGrids advisory council.